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PRINCIPLES OF PLASMA DISCHARGES AND MATERIALS PROCESSING

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1.3 DISCHARGES

Rf Diodes

Capacitively driven radio frequency (rf) discharges—so-called *rf diodes*—are commonly used for materials processing. An idealized discharge in plane parallel geometry, shown in Fig. 1.12a, consists of a vacuum chamber containing two planar electrodes separated by a spacing l and driven by an rf power source. The substrates are placed on one electrode, feedstock gases are admitted to flow through the discharge, and effluent gases are removed by the vacuum pump. Coaxial discharge geometries, such as the "hexode" shown in Fig. 1.12b, are also in widespread use. Typical parameters are shown in Table 1.1. The typical rf driving voltage is $V_{rf} = 100\text{--}1000$ V, and the plate separation is $l = 2\text{--}10$ cm. When operated at low pressure, with the wafer mounted on the powered electrode, and used to remove substrate material, such reactors are commonly called reactive ion etchers (RIEs)—a misnomer, since the etching is a chemical process enhanced by energetic ion bombardment of the substrate, rather than a removal process due to reactive ions alone.

For anisotropic etching, typically pressures are in the range 10–100 mTorr, power densities are 0.1–1 W/cm², the driving frequency is 13.56 MHz, and multiple wafer systems are common. Typical plasma densities are relatively low, $10^9\text{--}10^{11}$ cm⁻³, and the electron temperature is of order 3 V. Ion acceleration energies (sheath voltages) are high, greater than 200 V, and fractional ionization is low. The degree of dissociation of the molecules into reactive species is seldom measured but can range widely from less than 0.1% to nearly 100% depending on gas composition and plasma conditions. For deposition and isotropic etch applications, pressures tend to be higher, ion bombarding energies are lower, and frequencies can be lower than the commonly used standard of 13.56 MHz.

The operation of capacitively driven discharges is reasonably well understood. As shown in Fig. 1.13 for a symmetrically driven discharge, the mobile plasma electrons, responding to the instantaneous electric fields produced by the rf driving voltage, oscillate back and forth within the positive space charge cloud of the ions. The massive ions respond only to the time-averaged electric fields. Oscillation of the electron cloud creates sheath regions near each electrode that contain net positive

TABLE 1.1. Range of Parameters for Rf Diode and High-Density Discharges

Parameter	Rf Diode	High-Density Source
Pressure p (m Torr)	10–1000	0.5–50
Power P (W)	50–2000	100–5000
Frequency f (MHz)	0.05–13.56	0–2450
Volume V (L)	1–10	2–50
Cross-sectional area A (cm ²)	300–2000	300–500
Magnetic field B (kG)	0	0–1
Plasma density n (cm ⁻³)	$10^9\text{--}10^{11}$	$10^{10}\text{--}10^{12}$
Electron temperature T_e (V)	1–5	2–7
Ion acceleration energy E_i (V)	200–1000	20–500
Fractional ionization x_{iz}	$10^{-6}\text{--}10^{-3}$	$10^{-4}\text{--}10^{-1}$